On the extrapolation to ITER of discharges in pressent tokamaks

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An expression for the extrapolated fusion gain $G = P_{\rm fusion}/5P_{\rm heat}$ ($P_{\rm fusion}$ being the total fusion power and $P_{\rm heat}$ the total heating power) of ITER in terms of the confinement improvement factor (H) and the normalised beta (β_N) is derived in this paper. It is shown that an increase in normalised beta can be expected to have a negative or neutral influence on G depending on the chosen confinement scaling law. Figures of merit like $H\beta_N/q_{95}^2$ should be used with care, since large values of this quantity do not guarantee high values of G, and might not be attainable with the heating power installed on ITER.

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I. INTRODUCTION

In many tokamak devices discharge scenarios are studied with the aim of improving the performance of future reactor experiments over the current design values. Essentially two ingredients enter in the optimisation: the energy confinement time and the Magneto-Hydro-Dynamic (MHD) stability limit, represented by a critical pressure. Both energy confinement time and obtainable pressure are measured in current experiments and then for scaling purposes expressed in dimensionless parameters. The confinement improvement is given by the so-called H-factor which measures the energy confinement time (τ_E) relative to a scaling law ($\tau_{E,scaling}$). The obtainable volume averaged pressure ($\langle p \rangle$) is expressed in the normalised quantity β_N

$$H = \tau_{\rm E}/\tau_{\rm E,scaling} \quad \beta_{\rm N} = \langle \beta \rangle \frac{aB}{I_p}. \tag{1}$$

In the equations above $\langle \beta \rangle$ is the volume average of $2\mu_0 p/B^2$ measured in %, a is the minor radius in m, B is the magnetic field in T, and I_p is the plasma current in MA. For the extrapolation one assumes a constant H-factor and then uses the confinement scaling to determine the confinement time in a next step device. Furthermore, it is assumed that the working point of the reactor is at the same normalised pressure β_N. The H-factors describe our imperfect knowledge of the scaling of confinement, i.e. the confinement in current day experiments in some areas of the parameter space scales differently than the developed scaling laws suggest. Of course, the use of a constant H-factor is a daring approach to correct for this lack of knowledge, but nevertheless can give some idea of how confinement could be different in the next step experiment.

Different scenarios for improved performance have been proposed (see for an overview [1]). These scenarios include the internal transport barriers (ITB) as well as the different scenarios for the improvement of the H-mode. The results presented in this paper can in principle be applied to all scenarios, but as examples only the H-mode scenarios will be shown The latter scenarios are an active area of research with many contributions from different machines, for instance, ASDEX Upgrade [2], DIII-D [3], JET [4], and JT60-U [5]. (Although the original reference [2] refers to an internal transport barrier it was shown in a later paper [6] that the ion temperature profiles follow the same scaling as those of the standard H-mode).

An improvement in confinement or MHD stability would allow to operate the next step tokamak experiment ITER [7, 8] at a higher energy multiplication factor Q, a higher fusion power, or a higher bootstrap current fraction. We define the energy multiplication factor Q and the fusion gain G as

$$Q = \frac{P_{\rm fusion}}{P_{\rm aux}}, \qquad G = \frac{P_{\rm fusion}}{5P_{\rm heat}} \tag{2}$$

where $P_{\rm fusion}$ is the total fusion power, $P_{\rm aux}$ is the externally applied heating power, and $P_{\rm heat}$ is the total heating power of the plasma, which in steady state is equal to the loss power $P_{\rm loss}$. Since one fifth of the fusion power heats the plasma, $P_{\rm heat} = P_{\rm fusion}/5 + P_{\rm aux}$ and there is a direct relation between G and Q

$$G = \frac{Q}{Q+5} \tag{3}$$

The currently proposed next-step experiment ITER [8] is designed to reach $Q = 10$, and any realistic scenario to be tested in this experiment should reach a Q value significantly larger than one. Scenarios at sufficiently large Q might be further optimised to reach a higher fusion power, or to reach a higher bootstrap current fraction. The latter optimisation is known as the hybrid scenario. It aims at the extention of the pulse length at similar performance as the design value. It is important for the results presented in this paper to stress that improvements in fusion power or bootstrap fraction can only be of interest if the the energy multiplication factor is sufficiently high. In the opinion of the authors a good representation of the extrapolated performance of current

discharges towards ITER can only be obtained if one of the figures of merit is directly connected with Q. Other figures could be used to measure the bootstrap current and fusion power. Although Q plays a central role in the ITER experiment their is no published simple scaling that allows a direct assessment of the extrapolated value of current discharges. A simple way to obtain a rough estimate can be extremely useful in assessing the progress made in this large area of research. Finally, we would like to stress that our extrapolation formula aims at judging the performance in ITER and is not necessarily applicable for more general purposes. In particular we use a fixed size and magnetic field. A reactor design can also be optimised through changes in these parameters.

II. SCALING OF G

The fusion power is proportional to

$$P_{\rm fusion} \propto \frac{\langle \sigma v \rangle}{T^2} V\, p^2, \tag{4}$$

where T is the plasma temperature, V is the plasma volume, and $\langle \sigma v \rangle$ is the cross section for the fusion reactions averaged over the velocity distribution. Over the temperature range of interest $\langle \sigma v \rangle \propto T^2$, such that the fusion power scales with the pressure (p) squared. The power loss from the plasma ($P_{\rm loss}$) is measured by the energy confinement time τ_E, and under stationary conditions it is balanced by the total heating power

$$P_{\rm loss} = \frac{W}{\tau_E} = \frac{3pV}{2\tau_E} = P_{\rm heat}, \tag{5}$$

where W is the stored energy. Combining the Eqs (2), (4), (5), and (3) one obtains

$$G = \frac{Q}{Q+5} = \frac{P_{\rm fusion}}{5P_{\rm heat}} \propto nT\tau_E, \tag{6}$$

where $p = nT$ was used, and n is the plasma density. This is of course the famous $nT\tau_E$ product.

To proceed we write the confinement time as a product of the improvement factor H_X over the confinement time of an arbitrary scaling law (τ_X)

$$\tau_E = H_X \tau_X = H_X C_X\, I_p^{\alpha_I}\, B^{\alpha_B}\, P_{\rm loss}^{\alpha_P}\, n^{\alpha_n}\, M^{\alpha_M}\, a^{\alpha_a}\, \kappa^{\alpha_k}. \tag{7}$$

Here C_X is a constant, M is the effective mass in AMU, and κ is the plasma elongation. The exponents α are the exponents of the scaling law. For the projection to ITER the plasma size (a,R,κ) as well as the magnetic field B and the effective mass M are assumed to be given by the design values. For the density a fixed ratio of the Greenwald limit (n_{Gr}) [9] will be used, i.e. $n \propto n_{Gr} I_p$. In our final result it will not be difficult to obtain the result at constant density (i.e. the design value of the density without considering a scaling of this density with plasma current) since the density dependence that enters can be easily identified through the coefficient α_n, which can be set to zero to obtain the result for a given fixed density. Note that we cannot assume $P_{\rm loss}$ to be constant, since discharges at different beta will extrapolate to a different fusion power and, hence, to different plasma heating powers. Since for fixed magnetic field and plasma shape $I_p \propto q_{95}^{-1}$, with q_{95} being the safety factor at 95% of the plasma radius, and redefining the constant C_X to include all constant design quantities one obtains

$$\tau_E = H_X \tau_X = H_X C_X\, q_{95}^{-\alpha_I - \alpha_n}\, P_{\rm heat}^{\alpha_P} \tag{8}$$

Combining Eq. (8) with Eq. (6) one obtains an expression for G. Indicating all quantities of the ITER standard scenario with an index S, one can build the ratio

$$\frac{G}{G_S} = \frac{H_X}{H_{XS}} \frac{q_{95S}^{\alpha_I+\alpha_n}}{q_{95}^{\alpha_I+\alpha_n}} \frac{P_{\rm heat}^{\alpha_P}}{P_{\rm heat,S}^{\alpha_P}} \frac{p}{p_S} \tag{9}$$

Then recalling that $P_{\rm heat} = P_{\rm fusion}/5G$ and $P_{\rm fusion} \propto p^2 \propto (\beta_N/q_{95})^2$ one arrives at

$$\frac{G}{G_S} = \frac{H_X}{H_{XS}} \left(\frac{G}{G_S}\right)^{-\alpha_p} \left(\frac{q_{95S}}{q_{95}}\right)^{1+2\alpha_p+\alpha_I+\alpha_n} \left(\frac{\beta_N}{\beta_{NS}}\right)^{1+2\alpha_p} \tag{10}$$

Combining the terms containing G we finally derive at the desired expression

$$\frac{G}{G_S} = \left(\frac{H_X}{H_{XS}}\right)^{\frac{1}{1+\alpha_p}} \left(\frac{q_{95S}}{q_{95}}\right)^{\frac{1+2\alpha_p+\alpha_I+\alpha_n}{1+\alpha_p}} \left(\frac{\beta_N}{\beta_{NS}}\right)^{\frac{1+2\alpha_p}{1+\alpha_p}} \tag{11}$$

The figures of merit for different scalings can now be derived directly. Here the explicit expressions are given for four different scaling lows. The most commonly used IPB98(y,2) [7] indicated by τ_E^H, the L-mode scaling ITER89-P denoted by τ_E^L, a newly derived scaling from Ref. [10] denoted by τ_E^C, and an electro-static gyro-Bohm scaling law derived in [11] denoted by τ_E^{EGB}

$$\tau_E^H = 0.145 H_H I_p^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.39} a^{0.58} \kappa^{0.78} \tag{12}$$

$$\tau_E^L = 0.048 H_L I_p^{0.85} B^{0.2} P_{\rm heat}^{-0.5} n^{0.1} M^{0.5} R^{1.2} a^{0.3} \kappa^{0.5} \tag{13}$$

$$\tau_E^C = 0.092 H_C I_p^{0.85} B^{0.17} P_{\rm heat}^{-0.45} n^{0.26} M^{0.11} R^{1.21} a^{0.39} \kappa^{0.82}. \tag{14}$$

$$\tau_E^{EGB} = 0.0865 H_{EGB} I_p^{0.83} B^{0.07} P_{\rm heat}^{-0.55} n^{0.49} M^{0.14} R^{1.81} a^{0.30} \kappa^{0.75}. \tag{15}$$

In the equations above n is the density in units of 10^{20} m^{-3}, R is the major radius in m, a is the minor radius in m, M is the averaged ion mass in AMU, $\kappa = A/\pi a^2$ is the plasma elongation, A is the area of the poloidal cross section, and $P_{\rm heat}$ is in MW. The new scaling laws

(τ_E^C, τ_E^{EGB}) have been obtained after designed experiments have shown a small and possibly absent β dependence of the confinement [11, 12, 13, 14, 15] in contrast with the IPB98(y,2) scaling which, when expressed in normalised quantities (normalised pressure $\beta \propto nTB^{-2}$, normalised Larmor radius $\rho_* \propto \sqrt{T}/Ba$, and normalised collisionality $\nu_* \propto naT^{-2}$) has an unfavourable beta [7] dependence

$$B\tau_E \propto \rho_*^X \beta^Y \nu_*^Z \propto \rho_*^{-2.7} \beta^{-0.9} \nu_*^{-0.01}. \qquad (16)$$

For the electro-static gyro-Bohm scaling, therefore, zero beta dependence as well as $\tau_E \propto \rho_*^{-3}$ were imposed to derive

$$B\tau_E \propto \rho_*^{-3} \beta^0 \nu_*^{-0.14}. \qquad (17)$$

Several papers have pointed out the fact that the absence of the beta dependence in τ_E leads at high normalised pressure to more optimistic projections for ITER compared with IPB98(y,2) scaling [10, 15].

To obtain the scaling expressions for G a standard scenario must be defined. Here $q_{95S} = 3$ and $\beta_{NS} = 1.8$ will be used. The H-factors (H_{XS}) can be calculated by dividing the target confinement time by the confinement times of the scaling calculated using Eqs. (12), (13), (14), and (15). In the latter equations the ITER parameters ($I_p = 15$ MA, $B = 5.3$ T, $R = 6.2$ m, $\kappa = 1.75$, $n = 10^{20}$ m^{-3}, $a = 2$ m, $M = 2.5$, $P = 87$ MW, $\tau_E = 3.68$ s) are used, yielding $H_{HS} = 1.$, $H_{LS} = 2.2$, $H_{CS} = 1.07$, and $H_{EGB,S} = 0.8$. One then directly finds

$$G = CH^X q_{95}^Y \beta_N^Z. \qquad (18)$$

with the values of the constant C and the scaling potential giving in Table I. From this table it can be seen that β_N has a strongly negative effect in the IPB98(y,2) scaling, and a rather small effect in all the other scalings. It is clear from Eq. (11) that $G \propto \beta_N^0$ occurs only for the generic scaling $\tau_E \propto P^{-0.5}$.

For the derivation of a figure of merit one often approximates the coefficients of the scaling law. For a better comparison we can make the similar approximations, i.e. $\alpha_I = 1$, $\alpha_n = 0$, and $\alpha_p = -2/3$ for the IPB98(y,2) and $\alpha_p = -1/2$ for all other scaling laws. This yields

$$G = 10.8 \frac{H_H^3}{\beta_N q_{95}^2}, \qquad (19)$$

and

$$G = \gamma_X \frac{H_X^2}{q_{95}^2}, \qquad (20)$$

with

$$\gamma_L = 1.24 \quad \gamma_C = 5.25 \quad \gamma_{EGB} = 9.375. \qquad (21)$$

The figure of merit $H\beta_N/q_{95}^2$ can be considered a scaling for G if the exponents in the scaling law for the confinement are $\alpha_I = 1$, $\alpha_n = 0$, and $\alpha_p = 0$, i.e. only in the ideal condition if it is assumed that there is no power degradation. We note that one can define a figure of merit in different ways and that $H\beta_N/q_{95}^2$ can be thought of as a combination of good confinement, and high fusion power [16]. Also for the generic scaling ($\alpha_P = -0.5$) the bootstrap current in a reactor close to ignition scales as $H\beta_N$ [17]. It is, however, clear that $H\beta_N/q_{95}^2$ does not provide a figure of merrit for G. This point is important because it shows that one must be careful in using $H\beta_N/q_{95}^2$. From the scaling Eq. (19) it follows that the difference with the figure of merit $H\beta_N/q_{95}^2$ is $\propto (1.8H_H/\beta_N)^2$. The latter quantity is for discharges with normal confinement $H_H = 1$ but high normalised pressure $\beta_N = 3.6$ as small as 0.25. This makes a large difference in G. The above example with $H_H = 1$, $\beta_N = 3.6$, and $q_{95} = 4.2$ reaches a value for the parameter $H_H\beta_N/q_{95}^2$ that suggest that the ITER target ($Q = 10$) could be reached, whereas in reality such a discharges would extrapolate to $Q = 1$. Not only is this value of little interest, it also requires a rather large heating power, since the fusion power is four times larger and energy multiplication is much smaller. The other scaling laws suffer from the same problem, although it is less dramatic due to the different exponents of H as well as β_N.

TABLE I: Values of the constants of Eq. (18) for the different scalings. Both coefficients assuming ITER operation at fixed absolute density as well as at fixed Greenwald fraction ($n = 0.85n_{Gr}$) are given. The latter are indicated by the letters "Gr".

	C	X	Y	Z
IPB98(y,2)	9.62	3.22	-1.77	-1.23
IPB98(y,2) Gr	41.15	3.22	-3.19	-1.23
ITER89-P	0.892	2.0	-1.70	0
ITER89-P Gr	1.11	2.0	-1.90	0
Cordey	3.53	1.82	-1.72	0.18
Cordey Gr	5.94	1.82	-2.20	0.18
EGB	7.41	2.22	-1.62	-0.22
EGB Gr	24.52	2.22	-2.71	-0.22

III. DIMENSIONLESS VARIABLES

Some confusion can arise when considering the scaling in terms of the dimensionless parameters β, normalised Larmor radius $\rho^* = \rho/a$ and normalised collisonality ν^*. The scaling of G in terms of dimensionless parameters yields [15]

$$G \propto \beta(B\tau_E)B \propto \rho_*^{-1.5+X} \beta^{1.25+Y} \nu_*^{-0.25+Z} R^{-1.25} \qquad (22)$$

where X, Y, Z are the coefficient of the ρ_*, β and ν_* scaling of confinement as defined in Eq. (16). In the equation above the dependence on ρ_* as well as ν_* has been

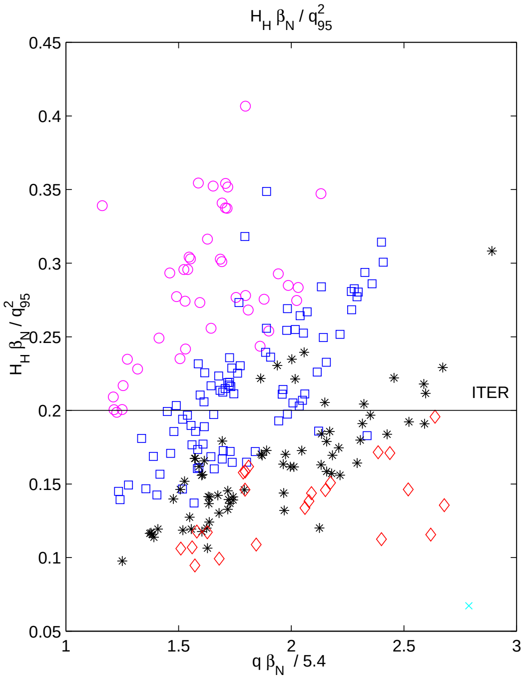

FIG. 1: (color online) Figure of merit $H_H\beta_N/q_{95}^2$ of the advanced scenario discharges from ASDEX Upgrade. The symbols correspond to different values of q: circles (magneta) $q < 3.5$, squares (blue) $3.5 < q < 4.0$, stars (black) $4.0 < q < 4.5$, diamonds red $4.5 < q < 5.0$, crosses $q > 5.0$

explicitly added compared with Ref. [15]. Using the scaling $G \propto \beta^{1.25+Y}$ it was concluded [15] that for the IPB98(y,2) scaling ($X = -0.9$) there is no large benefit of going to high β since Q increases only moderately with β ($\beta^{0.35}$), whereas for the energy confinement scalings that have no beta dependence it would be largely advantageous to go to the β limit since $G \propto \beta^{1.25}$. This conclusion seems in disagreement with the results derived in this paper, which rather point at a decreasing G with β_N for the IPB98(y,2) scaling and a G independent of β_N for the other scaling laws. Eq. (22) is the correct dimensionless expression, but it must be noted that the scaling with beta $G \propto \beta^{1.25+Y}$ holds only at constant normalised Larmor radius (ρ_*) as well as collisionality (ν_*). The difference with the results in this paper is that the results are evaluated for a fixed machine size, density, and magnetic field. With these assumptions it is not possible to change β independently of ρ_* and ν_*. At fixed density the β scaling is essentially a temperature scaling, leading to changes in the normalised Larmor radius as well as the collisionality. Using the scalings of ρ_* and ν_* one can derive from Eqs. (16), (17), and (22)

$$G_H \propto T^{-1.23} \qquad G_{EGB} \propto T^{-0.22}. \tag{23}$$

These scalings are consistent with the diagrams of Ref. [15] where G can be seen to decrease with increasing T even for the electro-static gyro-Bohm scaling. Therefore we arrive at the conclusion that for a given design reaching the beta limit does not help in increasing G. Of course the density scaling is more hidden in our approach since it is considered to be a design value. One can derive that G increases strongly with density for all scalings.

Finally, it is noted here that for constant heating power $\beta_N \propto H$ and all figures of merit have the same form

$$\frac{H\beta_N}{q_{95}^2} \rightarrow \frac{H^3}{\beta_N q_{95}^2} \rightarrow \frac{H^2}{q_{95}^2} \tag{24}$$

IV. PERFORMANCE DIAGRAM

Having derived a simple expression that directly allows to evaluate G, a suggestion is made in this section for a diagram that should allow for an easy assessment of the extrapolated performance of any discharge. From the discussion above it is clear that a better representation of the data can be obtained by plotting the scaling for $G = Q/(Q+5)$. against either the scaling of the fusion power, i.e. β_N^2/q_{95}^2, or the scaling of the bootstrap current, i.e. $q_{95}\beta_N$. Since both are of importance it is useful to mark the different q_{95} values by different symbols in whatever plot one chooses. This makes that all important parameters can be estimated from the same graph.

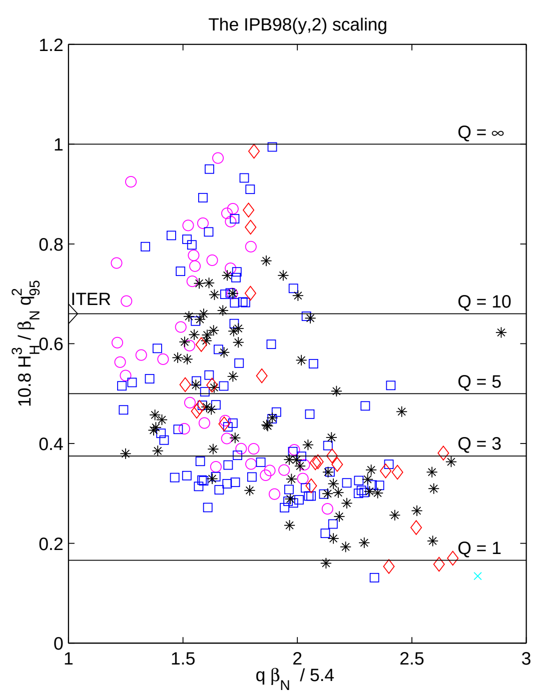

FIG. 2: Fig. 2 (color online) Scaling for the advanced scenario discharges based on the IPB98(y,2) scaling. Symbols reflect the q_{95} values as in figure 1.

Figure 1 shows a dataset of advanced scenario discharges from ASDEX Upgrade in the representation using $H_H\beta_N/q_{95}^2$ versus $q_{95}\beta_N$. In this figure the different q_{95} values are indicated with with different symbols (and colours in the online version). In the representation using $H\beta_N/q_{95}^2$ even the points at highest $q_{95}\beta_N$ reach the ITER target.

Figure 2 shows the scaling derived from Eq. (19). This can be directly compared with Fig. 1 since the same scaling law is used. The obtained picture is different in the sense that the highest $q_{95}\beta_N$ values no longer reach the ITER target for Q. These discharges have only moderate confinement improvements and high β_N leading to a relatively small $(H_H/\beta_N)^2$. In the diagrams Q can exceed infinity, which is obviously unphysical. For those discharges for which $Q > \infty$, the temperature will rise until the fusion cross section no longer scales quadratically with T, violating the original assumptions in the derivation, and leading to a smaller increase of the fusion power with T. This stabilises the solution and leads to $Q = \infty$.

In the diagrams presented so far the external heating power is still implicit. A better insight of how much external heating power is needed to run a certain discharge under reactor conditions can be obtained from the diagram that has the scaling of the fusion power $P_{\text{fusion}} \propto (\beta_N/q_{95})^2$ on the x-axis. Because $P_{\text{aux}} = P_{\text{fusion}}/Q$ one obtains

$$P_{\text{aux}} \propto \frac{1}{Q}\left(\frac{\beta_N}{q_{95}}\right)^2. \qquad (25)$$

For a fixed auxiliary heating power the relation above determines a curve in the $G = Q/(Q+5)$ versus $(\beta_N/q_{95})^2$ diagram. Figure 3 shows the same data as the diagrams before, plotting $G = Q/(Q+5)$ versus the fusion power normalised to the ITER value $2.77(\beta_N/q_{95})^2$. The dashed lines in this diagram are the different values of the auxiliary heating power. From left to right 1, 2, 4, and 8 times the ITER design value. This diagram shows that high pressure discharges at low Q values would require a large amount of installed heating power to be run. It is this diagram that carries the largest amount of information and we propose it to be used when representing larger datasets of advanced scenario discharges.

The diagrams presented in this paper are far from perfect, with several effects not properly accounted for: Radiated power due to Bremsstrahlung as well as dilution of the fuel are not properly scaled. The approach with constant H-factor and β_N is always daring for an extrapolation. If better MHD stability is, for instance, reached through current profile shaping, then one should investigate if such a shaping is extrapolatable to reactor parameters. Also, although β_N is a good scaling quantity for ideal MHD instabilities, it does not provide a very good scaling for the NTM, which is often found to limit the attainable beta. Nevertheless for the representation of large data sets these diagrams are certainly useful. Also they give an idea of what parameters are important when developing scenarios.

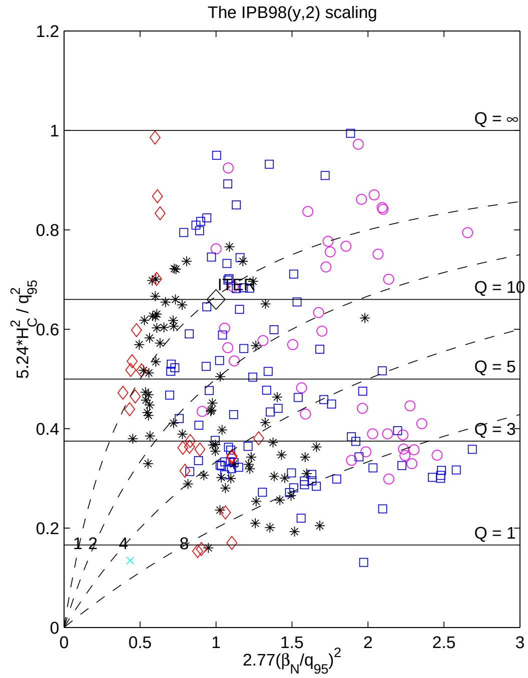

FIG. 3: (color online) Extrapolated values of $Q/(Q+5)$ as a function of the normalised fusion power $2.77(\beta_N/q_{95})^2$. Symbols reflect the q_{95} values as in figure 1. The dotted lines indicate the amount of external heating (P_{aux}) necessary to run the discharge in ITER. From left to right the curves correspond to power levels 1, 2, 4, and 8 times the nominal ITER value

V. CONCLUSIONS

In this paper a scaling for tokamak discharges is derived that directly measures the fusion gain $G = Q/(Q+5)$, and which are consistent with the underlying scaling laws. It is shown that β_N does not have a positive influence on G, although it does of course extrapolate to a larger fusion power. Care is to be taken with figures of merit like $H\beta_N/q_{95}^2$. Although this figure of merit does measure a combination of good confinement and high fusion power, the ITER target value of such a quantity does not automatically imply a discharge with a sufficiently high Q, and might not be attainable with the limited heating power that will be installed. A proposal is made for a graphical representation in which both the extrapolated Q as well as the fusion power or the bootstrap fraction can be directly assessed.

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